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Management and Control of two-and three-dimensional separated flows by unsteady and/or vortical flows is investigated in a number of configurations aimed at an enhanced basic understanding of governing mechanisms. The investigations are aimed at impacting the design of future generations of aircraft with improved maneuverability for better performance and safety. Also, novel techniques are being developed for the measurement, mapping and documentation of these complex unsteady flowfields.

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CONTROL AND SCALING OF FORCED UNSTEADY SEPARATED FLOWS

Locally introduced unsteady vorticity resulting in the forced reattachment of separated flows was achieved in prototype experiments involving two different model separated flows. The computer controlled oscillations of a two-dimensional spoiler-like flap placed inside the separated zone of the flow were used to obtain premature reattachment. The effects of the flap motion were studied over reduced frequencies ranging from 0.0067 to 0.2400, and for Reynolds numbers based on the momentum thickness of the approach boundary layer ranging between 500 and 4,000. In particular, based on the results of this study, the following conclusions can be drawn: a) the mean reattachment length of the flow decreases with increasing amplitudes of the flap motion, provided that the tip of the flap does not reach outside the shear-layer; b) low duty cycle wave forms of the flap motion provide the most effective control at low reduced frequencies, whereas, for $k < 0.04$ high duty cycle wave forms are necessary to hold vortices longer at the flap; c) most efficient control is obtained when the oscillating flap is placed in the immediate downstream vicinity of the point of separation of the flow; d) most importantly, the forced unsteady flow configurations that were studied throughout this investigation scale with reduced frequency. The results of this study indicate that the flowfields investigated scale with reduced frequency, and that an optimum in terms of reattachment control is obtained for reduced frequencies $0.05 < k < 0.10$.

Results were obtained for three heights of the separation generator, using several freestream velocities and numerous forcing frequencies. The dynamical scaling analysis of reattachment control as a function of reduced frequency revealed the existence of at least two distinct mechanisms controlling flow reattachment. At low reduced frequencies ($k <$ 0.0[illegible]), the primary mechanism corresponds to the momentum exchange induced by the modulation of the separated shear layer, and leads to the periodic shedding of the separation bubble. This mechanism scales with the characteristic height of the separation region. For larger values of the reduced frequency parameter, the dominating mechanism is the formation and shedding of energetic vortices caused by the oscillation of the flap. This mechanism scales with the reduced frequency based on the flap height.

VORTEX INTERACTION WITH SOLID SURFACES

An investigation of vortex interaction with solid surfaces was performed. The impinging, or primary, vortex ring was embedded in the shear layer of a forced axisymmetric water jet at a Reynolds number based on diameter and mean velocity at the jet exit of 2500 and a forcing Strouhal number of 0.45. The primary vortex/surface interaction was studied as a function of mean pressure gradient by varying the impingement angle; a flat plate and three cones of vertex angle 45°, 30°, and 15° were considered. Flow-visualization records showed the formation of an induced vortex underneath the primary vortex and next to the solid surface which rotates in the opposite sense of the primary vortex, and a downstream-moving separation. The location along the solid surface at which the induced vortex was first observed was found to move upstream with decreasing mean pressure gradient, supporting the hypothesis that the favorable mean pressure gradient provided by the solid surface must be exceeded by the adverse unsteady pressure gradient carried with the primary vortex for separation to commence. The primary and induced vortices progress along the surface of the wall in close proximity, interacting in a inviscid manner, as the induced vortex grows in size and strength. At multiple downstream locations on each surface, a portion of the induced vorticity at the wall was torn away from the boundary layer and wrapped around the primary vortex in a phenomenon called breakaway. Phase-averaged quantitative measurements confirmed the multiple locations of breakaway seen in the flow visualization and provided important clues as to the characterization of the separation and breakaway process. A local phase-averaged displacement thickness maximum convects downstream with the induced vortex and grows in magnitude until breakaway. A band of zero-shear stress was observed to slice the induced vortex as it develops prior to breakaway.

CONTINUED AND FUTURE RESEARCH

More recently, we have been pursuing investigations in several specific areas described below. The overall objectives are to develop the techniques and capability for the prevention or control of separated flows, particularly under unsteady operating conditions, and the control of unsteady forces and moments on various configurations.

The facilities of the FDRC include the capability to generate controlled time-varying flow fields (in both the A.A. Fejer wind tunnel and the National Diagnostic Facility) and to map flow fields with a variety of tools including the two-component LDA, tomographic flow visualization, scanning LDA, multi-probe hot wire systems and Scanivalue pressure systems. Together with the sophisticated data acquisition and presentation capabilities available at the center, they provide a unique infra-structure that facilitates this program of work.

A. Active control of separated flow about airfoil geometries

Current experiments to obtain reliable pressure signatures of separation (or incipient separation) in unsteady flow fields over basic geometries are yielding results that will help identify appropriate indicators of flow state in an unsteady separated flow. The results from these experiments will be used to examine the feasibility of active control of separated flows over airfoil geometries in pitching motion. The study will focus initially on a 2D symmetric airfoil but will be extended to 3D geometries. (The latter will include delta wings and finite swept wings at an angle of attack.) A variety of approaches to effect the control will be investigated, including suction, leading edge flaps and slats, and techniques to introduce transverse or streamwise vorticity in the flow field at appropriate points. In addition, the unsteady forcing technique described in (B) below will also be explored (as a means of controlling the base flow region). A natural extension of the active control experiments will be to investigate the possibilities of reactive control with feedback.

B. Unsteady, zero mass base bleed

Experiments at IIT have demonstrated the effectiveness of the unsteady base bleed technique for modifying the flow around bluff bodies. This method uses unsteady pulsating jets with zero net mass addition to modify the flow field. The effectiveness of the technique has been demonstrated on the wake behind circular cylinders for flow at low Reynolds numbers. At the proper frequency and amplitude, the wake momentum thickness was reduced to zero which means the drag has been essentially eliminated.

The unsteady base bleed technique is attractive from the design standpoint because no net mass is added to the flow, and the body itself does not move. This means it is not necessary to carry a supply of bleed fluid, or pay any drag penalty associated with suction ports. Furthermore, the unsteady base bleed can be turned on and turned off as desired, and variations in frequency and amplitude cause variations in the level of control. In this way it is possible to tailor the amount of flow control with the unsteady base bleed technique.

C. Unsteady Vortex System About Axisymmetric slender body/forebody geometries

Experiments are now underway to examine the unsteady flow about a slender body of circular cross section with a conical forebody, as it undergoes an unsteady motion. By increasing the major/minor axis ratio (aspect ratio) of cylinders with elliptical cross-sections, we can observe the change in the vortex structure as the geometry changes from a circular cylinder to a flat plate.

The elliptical cross-sections are closer approximations to modern aircraft forebodies, and we expect to find more complex flow behavior during a pitching motion than with the simple circular cylinder. For example, the boundary layers attached to the different geometries will experience different development histories before reaching the separation line. Certainly different regimes of vortex behavior such as a steady system of vortices or unsteady shedding will be encountered as each body pitches. The tomographic flow visualization currently under development will be used to map the different regimes. An attempt will be made to collapse the data on the basis of aspect ratio. Quantitative information are obtained when necessary using LDA measurements.

D. Scanning Laser Anemometer

Very often it is necessary to obtain spatial correlations, wavenumber, phase distributions or other spatial quantities in order to describe the spatial character of disturbances found in both laminar and turbulent flow fields. For example, symmetric-antisymmetric mode competition in wakes, secondary instability in jets, wakes and boundary layers, and coherent structures in turbulent flows require spatially detailed information in order to be accurately described. However, it is difficult to obtain spatial information with stationary, single-point measuring techniques like the hot-wire anemometer and laser anemometer. Basically, one has the choice of constructing rakes of probes, using a flying hot-wire or using some type of conditional sampling technique. The first two choices tend to disturb the flow and rakes of probes have limited spatial resolution. All conditional sampling techniques require averaging, which "smears" the event to be detected. The scanning laser anemometer attempts to overcome these limitations by its nonobtrusive nature and its ability to sample an area in the flow at very high speed. Provided a region in space can be sampled much faster than the rate of change of the flow field, then a quasi-instantaneous velocity map can be obtained. From this data base the spatial correlations, spatial phase, spectra, etc. may be computed. Additional details of the optical components of the system can be found in the thesis by Economou(1986).

The scanning laser anemometer system has been used successfully to make multiple-point, quasi-instantaneous measurements in wakes behind bluff bodies and in highly unsteady, pulsating jets. The system offers good temporal/spatial resolution over a wide range in the flow. The use of the scanning system played a major role in the development of the zero-mass base bleed technique. Our efforts are currently focussed on developing new software to acquire and display the data during scanning over an area. Furthermore, some effort needs to be spent on development of new data processing techniques to describe the two-dimensional fields of data already acquired while scanning over a line.

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